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ORIGINAL PAPER

An approach to cork oak forest management planning: a case study in southwestern Portugal

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Abstract This paper presents results of research aiming at the development of tools that may enhance cork oak (*Quercus suber* L.) forest management planning. Specifically, it proposes an hierarchical approach that encompasses the spatial classification of a cork oak forest and the temporal scheduling of cork harvests. The use of both geographical information systems and operations research techniques is addressed. Emphasis is on the achievement of cork even flow objectives. Results from an application to a case study in the Charneca Pliocénica of Ribatejo in southern Portugal encompassing a cork oak forest extending over 4.8 thousand ha are discussed. They suggest that the proposed approach is capable of effective spatial classification of cork oak management units. They further suggest that it may be used to select optimal cork even flow scheduling strategies. Results also show that the proposed approach may lead to a substantial increase in net present value when compared to traditional approaches to cork oak forest management planning.

Keywords *Quercus suber* L. · Cork oak forest management · Linear programming · Cork harvesting · Harvest scheduling

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Introduction

Cork oak (*Quercus suber* L.) is the second most important Portuguese forest species extending over about 737 thousand ha (which corresponds to 23% of total Portuguese forest area; DGRF 2007). Cork oak forests are mainly located in southwestern Portugal. Often they are part of multiple use agro-forestry-pastoral ecosystems called "*montados*" characterized by a scattered tree cover and activities such as grazing, fallow or pastures under the oak canopies (Barbero et al. 1990; Joffre et al. 1999; Pinto-Correia and Vos 2004). In this non-wood forest product system, cork harvesting is the major economic activity as cork is still the most valuable product and the main source of income (Montero and Cañellas 2003; Pereira and Tomé 2004).

Cork management planning is somewhat different from timber management planning. The first cork harvest typically occurs when the tree is over 20 years of age. Afterward, cork is usually harvested every 9 years over the whole tree life cycle (Montero and Cañellas 2003; Pereira and Tomé 2004). Cork oak silviculture thus adds complexity to the traditional forest management problem focusing on timber (Falcão and Borges 2005). Borges et al. (1997) reported results of the first quantitative approach to cork oak forest management planning. Yet traditional approaches to regulation are still predominant.

Results from research on cork oak silviculture and growth and yield modeling have been recently reported (Tomé et al. 1999; Cañellas and Montero 2002; Costa et al. 2002; Paulo et al. 2002; Sánchez-González et al. 2005, 2006) that are instrumental to support cork harvest scheduling decision analysis. They enhance the capability to predict long term cork oak growth and the variability associated to different climate scenarios. Borges et al.

(2003), Ribeiro et al. (2004) and Falcão and Borges (2005) demonstrated the potential of decision support systems to further enhance cork oak forest management scheduling.

This paper builds upon most recent research to develop an innovative hierarchical approach to cork oak forest management. The proposed approach combines the use of geographical information systems (GIS) and quantitative techniques to address cork harvest scheduling operational spatial goals and strategic even flow objectives. Specifically, using GIS and a linear programming model to maximize net present value (NPV), optimal land unit areas are assigned to scheduling strategies that comply with even flow constraints over a 9-year cycle. Results are reported from an application to a case study in the Charneca Pliocénica of Ribatejo in southern Portugal encompassing a cork oak forest extending over 4.8 thousand ha.

Materials and methods

The study area

The study area is located in a state-owned farm extending over 11 thousand ha in Charneca Pliocénica of Ribatejo in the Portuguese sub-mediterranean ecological region (Fig. 1). The cork oak forest area extends over 4.8 thousand ha (about 43% of the farm total area) and is currently classified into nine heterogeneous and contiguous management units based on administrative boundaries, main roads or water lines. Management unit area ranged from 154 ha (unit 9-SI0) to 1.0 thousand ha (unit 6-MA0).

In order to generate information needed for management planning, the cork area was inventoried using a systematic sampling design and a line plot system defined by compass lines established at a uniform spacing of 500 m. At 500 m intervals, 2,000 m^2 circular plots were located along these lines as suggested by several authors for the same region (Ribeiro 1990; Costa 1990; Borges et al. 1997). A total of 313 plots were measured corresponding to a sample area of 60.4 ha (1.5% of the forest area). Each permanent plot was represented by a point in a spatial mesh of a GIS linked to a relational data base that stored the plot attributes. Other GIS layers included the cork management unit limits, the cork oak forest area limits and the limits of areas with the same cork age.

All trees with circumference at breast height (CAP) equal or superior to 70 cm were measured in each cork oak plot. Primary tree data included the cork oak circumference ($CAP_{1.30}$, m), the cork stripping status (virgin or debarked) and the cork extraction year (Year). The first cork harvest takes place when the tree perimeter at breast height reaches 70 cm. Thus, cork oak debarking usually starts at the age of 25–30 years (Falcão and Borges 2005). Derived stand-level data included the number of trees per hectare that had already been debarked (N); the maximum circumference at breast height $CAP_{max1.30}$ (m); the mean circumference at breast height, $CAP_{mean1.30}$ (m) and the basal area of trees that had already been debarked (G, m^2).

Current legislation prescribes a minimum cork harvest cycle of 9 years in any given tree. Cork yield estimates in areas where cork age was 9 years were based on a model developed for the same area by Costa (1990). As other approaches (e.g., Montero 1987; Montero et al. 1996; Cañellas and Montero 2002), this model predicts cork yield at 9 years of age as a linear function of the stand basal area. In the case of other areas, first a model developed by Costa et al. (2002) was used to estimate basal area when cork age will reach 9 years. Secondly, the model developed by Costa (1990) was used to estimate cork yield.

The average cork productivity is 2.0 ton ha^{-1} corresponding to a relatively high productivity when compared with the mean regional productivity of 1.6 ton ha^{-1} (DGF 2001). Yield estimates further demonstrated the heterogeneity of current cork management units (Table 1). Cork productivity ranged from 1.3 to 3.1 ton ha^{-1} in units 9-SI0 and 8-RO0, respectively. In some units, four or five cork ages might be found (e.g., unit 1-AZ0 and unit, 6-MA0, respectively).

As a consequence, annual cork flows within the 9-year cork growth cycle would be very irregular if no changes were made to traditional practices (Fig. 2). For example, cork harvests in areas where current cork age is 5 years would amount to 1,818 ton. Yet in areas where current cork age is 7 years total harvest would amount to 606 ton. Further, cork areas where cork age is 5 years extend over 784 ha distributed per four units (1-AZ0, 4-CA1, 5-CA0

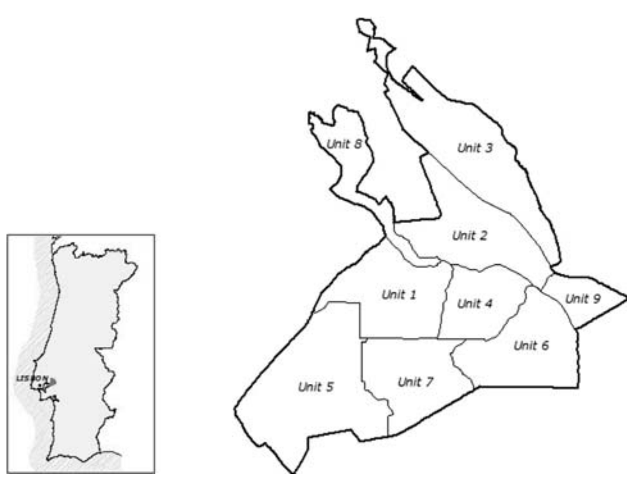

Fig. 1 The location of the state-owned farm area divided into nine heterogeneous cork management units: unit 1-AZ0, unit 2-BA0; unit 3-BE0; unit 4-CA1; unit 5-CA0; unit 6-MA0; unit 7-PO0; unit 8-RO0 and unit 9-SI0

Table 1 Current cork management units. Distribution of area per cork age and cork yield classes

Cork management unit	Total area (thousand ha)	Cork oak area (ha)	Cork age (years)	Cork oak area by cork age (ha)	Cork oak area (ha) by cork yield classes (ton ha^{-1})						Cork oak productivity (ton ha^{-1})
					<0.75	0.75–1.50	1.50–2.25	2.25–3.00	3.00–3.75	>3.75	
AZ0-unit 1	1.3	578	9	106	2	23	38	0	14	29	2.3
			8	131	11	30	34	0	19	37	
			5	336	37	55	65	82	79	18	
			1	5	0	0	0	0	5	0	
BA0-unit 2	1.4	804	8	211	73	69	23	46	0	0	1.4
			7	402	68	181	94	20	20	20	
			2	190	42	81	14	40	14	0	
BE0-unit 3	1.8	497	8	213	40	32	32	28	16	64	2.1
			4	284	9	23	215	37	0	0	
CA1-unit 4	0.8	484	5	15	4	1	3	4	0	3	2.2
			8	4	1	2	1	0	0	0	
			1	464	0	130	130	112	56	37	
CA0-unit 5	2.2	295	9	66	0	33	0	33	0	0	1.5
			5	180	72	33	33	14	29	0	
			2	50	16	17	17	0	0	0	
MA0-unit 6	1.3	1011	6	0	0	0	0	0	0	0	2.2
			4	263	38	56	19	75	56	19	
			3	387	17	101	50	118	101	0	
			2	270	35	24	59	83	35	34	
			1	91	54	19	0	0	0	18	
PO0-unit 7	1.1	728	9	127	0	20	49	39	10	10	2.3
			6	559	14	90	138	152	124	41	
			4	43	34	9	0	0	0	0	
RO0-unit 8	0.7	253	5	253	0	15	30	74	59	74	3.1
SI0-unit 9	0.4	154	6	154	34	69	34	17	0	0	1.3

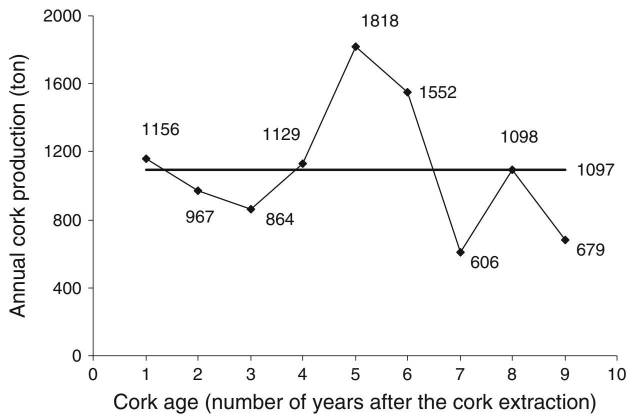

Fig. 2 Annual production of cork (ton) of the cork oak stand in the 9-year cork production cycle. Mean annual cork yield is 1,097 ton

and 8-RO0) and areas where cork age is 7 years extend over 402 ha only in one unit (2-BA0; Table 1).

The cork oak forest management problem

Cork age heterogeneity within a management unit lead to spatial dispersion of cork harvest schedules in any given year. Operational concerns suggested the spatial concentration of harvesting. Further, cork productivity heterogeneity between management units complicated the design of optimal cork even flow strategies over the 9-year cork growth cycle. Thus, the cork oak forest management problem encompassed two main objectives.

First, nine new equally productive and contiguous management units should be designed to address operational concerns and to provide the geographical basis for an area-control approach to regulation. A GIS was used to define units equally productive. Former units boundaries were preserved as much as possible and the definition of the nine new units took also into account the road network and natural limits.

The second objective was the optimization of cork harvest scheduling subject to even flow constraints. It was assumed that during the spatial conversion period, the period needed to achieve the cork age homogeneity condition in the new units, cork might be harvested with age ranging from 8 to 11 years and that changing the cork growth cycle would not impact tree productivity or cork price. A wide range of potential conversion periods for each management unit was considered. A simulator was used to generate all cork harvest schedules that might meet the age homogeneity condition in each management unit in each conversion period. Cork harvest schedules net present values were computed considering a 3% discount rate. This provided the information needed to select the optimal cork harvest schedule for each management unit and conversion period.

The cork harvest scheduling problem may be represented as an assignment model (Borges et al. 1997):

$$\text{Maximize } Z = \sum_{i=1}^{n} \sum_{t=y}^{y+8} c_{it} x_{it} \tag{1}$$

subject to:

$$\sum_{i=1}^{n} x_{it} = 1\ ,\ \ t = y,\ y+1, \ldots\ldots, y+8 \tag{2}$$

$$\sum_{t=y}^{y+8} x_{it} = 1\ ,\ \ i = 1,\ 2.\ldots.., 9 \tag{3}$$

with $x_{it} = 0 \vee 1, \forall i, t$ where, i is the management unit identifier. n is the number of management units (nine).y is the first year of the earliest 9-year period in which the constraints may be met, e.g., $y + 8$ corresponds to the minimum conversion period for the whole forest area.c_{it} is the maximum discounted revenue produced from management unit i when the age homogeneity condition is satisfied in year t.x_{it} is a binary variable that is set equal to 1 if the age homogeneity condition in management unit i is satisfied in year t and to 0 otherwise.

Equation 1 expresses the management objective of maximizing cork present value. Equation 2 ensures that each management unit will be assigned to a different cork extraction year within a 9-year period. Equation 3 ensures that cork extraction from all trees in a management unit will occur in the same year (age homogeneity condition).

Results

Based on inventory data and on the cork yield estimates, the mean annual cork production within a 9-year cork production cycle may be computed as 1,097 ton year^{-1} (Fig. 2). If all forest area was equally productive (and considering the average cork productivity is 2.0 ton ha^{-1}), the mean annual cork flow would result from harvesting 549 ha every year. Nonetheless current units are not equally productive. For example, to meet the 1,097 ton - year^{-1} target, just 477 ha would need to be harvested in the case of management unit 7-PO0. The productivity of current units provided information needed to design the nine new equally productive and contiguous management units.

The cork management unit 9-SI0 would the most impacted by landscape design. About 700 ha had to be added to this unit in order to meet the mean annual cork production target. Conversely, cork management unit 3-BE0 would the least impacted as adding 25 more ha was enough to meet that target. The actual reorganization and reclassification of the farm land into the new nine cork management units was made with GIS support. Maps with current units' boundaries and features such as roads and rivers were overlaid to help design the new units. Specifically, this overlay was used to select both the boundaries to change and the areas to add or to remove from all units so that all new units might approximate the equal productivity goal.

The landscape design process was effective. All units except for cork management unit 3-BE0 were redesigned. For example, the new unit 5-BA0 resulted from decreasing the cork oak area of former unit 2 from 804 ha to 775 ha. Conversely, the cork oak area of unit 9-SI0 increased from 154 to 578 ha. The unit whose productivity deviated the most from the mean annual cork production target was new cork management unit 7-CA0 (former unit 4). Yet, even in this case, the deviation amounted to 2.3%, i.e., about 26 ton and this was acceptable for decision makers.

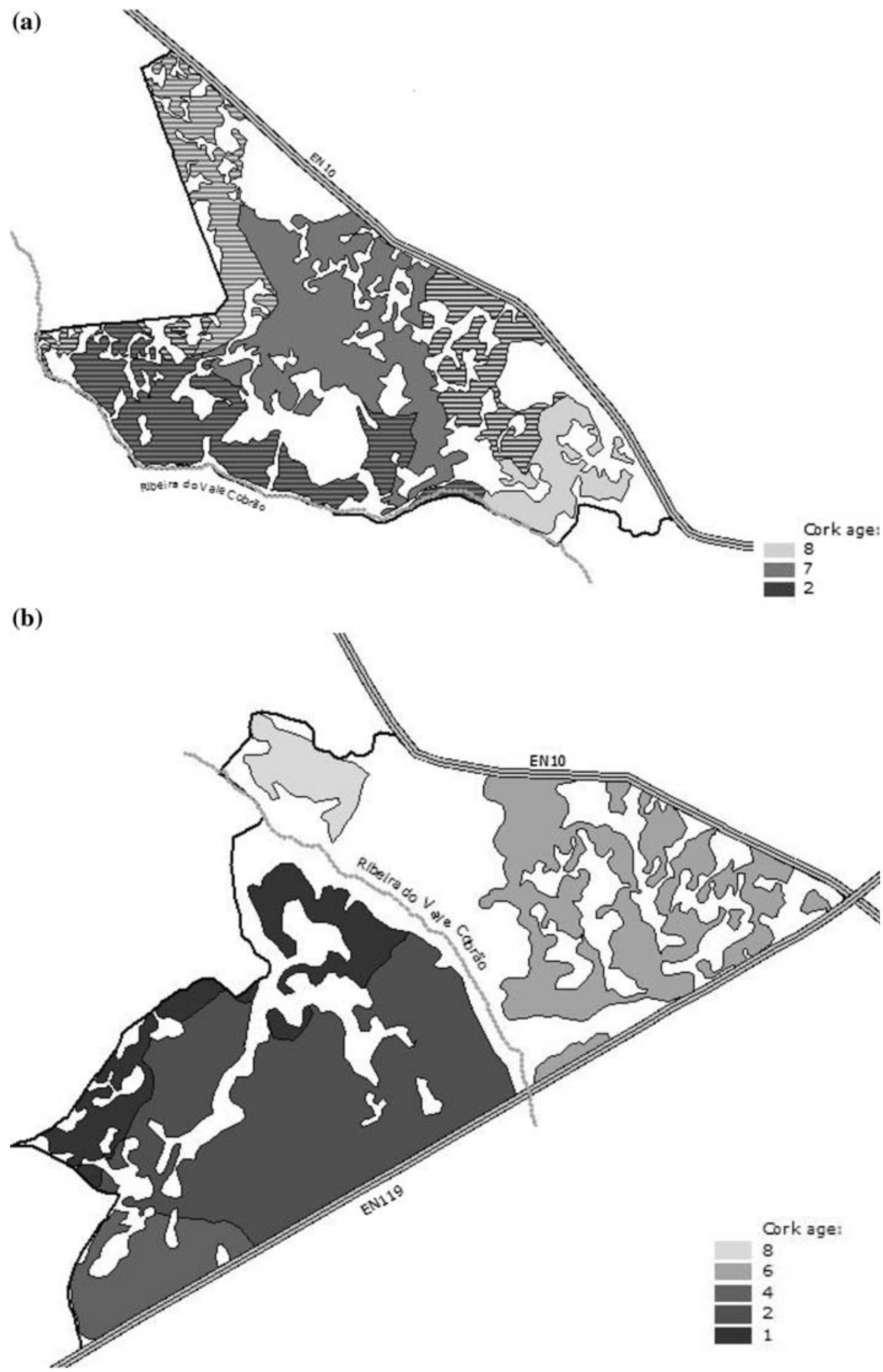

Fig. 3 The new boundaries of cork management units: **a** unit 5-BA0 (former cork management unit 2-BA0) with mixed cork age classes: cork ages 8 and 7 ; cork ages 8 and 2 ; cork ages 7 and 2 ; **b** unit 9-SI0 (former cork management unit 9-SI0)

Table 2 Total number of feasible cork harvest schedules for cork management unit 9-SI0. The minimum conversion period is about 18 years

Conversion period (years)	Cork age (years)					Total number of cork extraction schedules
	8	2	4	6	1	
18	3	3	1	1	4	12
19	6	2	**0**	3	3	**0**
20	9	1	1	6	2	19
21	10	**0**	3	10	1	**0**
22	9	1	6	11	**0**	**0**
23	6	3	10	11	1	31
24	3	6	12	9	3	33
25	2	10	12	5	6	35
26	3	12	10	3	9	37

In bold are the unfeasible conversion time horizons

Landscape design impacted the distribution of units' area per cork age. For example, in the case of unit 9-SI0, only one age class was present before the unit redesign (Table 1). Yet afterward, this unit area was distributed per 5 age classes (Fig. 3b). The conversion period needed to meet the cork age homogeneity condition was thus unit dependent.

The simulation of cork harvest schedules was instrumental to assess when a specific unit might meet the cork age homogeneity condition. For example, in the case of cork management unit 9-SI0, the minimum conversion period extended over 18 years. Yet conversion time horizons extending over 19, 21 and 22 years were not feasible as no cork schedules might be found for areas with cork age equal to 4, 2 and 1 years, respectively, that might meet the homogeneity condition (Table 2). This information provided the basis to define Y, the first year of the earliest 9-year period in which the constraints may be met, in Eqs. 1 and 2.

The simulation of cork harvest schedules was also instrumental to select the optimal schedule for each conversion period in each unit. This selection involved the computation of harvest schedules net present value considering a perpetual 9-year series of cork harvests after the homogeneity condition was met.

For instance, in the case of unit 2-RO0 (former unit 8), there are areas where the cork age is equal to 5 years and areas where the cork age is equal to 8 years. Thus, the schedule simulated for a conversion period extending over 20 years encompasses cork harvesting in years 1 (in areas with current cork age equal to 8 years), 3 (in areas with current cork age equal to 5 years), 10 (in areas with current cork age equal to 8 years), 11 (in areas with current cork age equal to 5 years) and 20 (in areas with cork age equal to 5 or 8 years; Table 3).

Nevertheless, in the case of this unit, the optimal schedule met the age homogeneity condition in year 13. Its net present value was equal to 10,958 thousand euros (Table 4). It encompassed cork harvesting in the years 3 and 13 corresponding to a number of years between two consecutive cork extractions of 11 and 10, respectively (for cork age equal to 8 years). It further encompassed cork harvesting in the years 4 and 13 corresponding to a number of years between two consecutive cork extractions of 9 (for cork age equal to 5 years).

The simulation of cork harvest schedules and the computation of its net present value thus provided all information needed to run the assignment model. Y is equal to 12 and the overall conversion period will extend to 20 years (Table 3). The solution of the assignment model selected the conversion period and the corresponding cork harvest schedule for all nine new units (Table 4).

The objective function value for the solution of the assignment model takes the value of 101,400 thousand euros (Table 4). This value is higher than the one associated to current management practices. The latter has been estimated to be 78,200 thousand euros. Current practices involve cork harvest schedules every 9 years and do not address regulation concerns. The possibility of harvesting cork with 8 years of age during the conversion period explains the difference of about 4.8 thousand euros per ha. Further, the proposed approach met both the strategic even flow goal and the operational concern with spatial dispersion of cork harvest scheduling in any given year. At the end of the overall conversion period, all management units will be cork even aged and each will be harvested in unique year in the 9-year cork harvest cycle (Fig. 4).

Discussion

Linear programming (LP) has been mostly used for strategic forest management planning (e.g., Dykstra 1984; Hoganson and McDill 1993; Davis et al. 2001; Buongiorno and Giless 2003). Typically, decision variables correspond either to prescriptions assigned to stands or to rotations assigned to areas with the same productivity and in the

Table 3 Cork management unit's conversion period

Cork management units	Conversion period (years)								
	12	13	14	15	16	17	18	19	20
1-AZ0	0	0	0	0	0	1 (6,8,9,17)	0	1 (1,3,8,10,11,19)	1 (1,3,9,10,11,20)
2-RO0	1 (1,3,12)	1 (3,4,13)	1 (3,14)	0	0	1 (1,6,9,17)	0	1 (1,3,10,11,19)	1 (1,3,10,11,20)
3-BE0	1 (1,4,12)	1 (3,4,13)	1 (3,14)	0	0	1 (1,6,9,17)	1 (1,7,9,18)	0	1 (1,4,9,12,20)
4-CA0	0	0	0	0	0	0	0	1 (1,2,3,8,9,10,11,19)	1 (1,2,3,9,10,11,20)
5-BA0	0	0	1 (3,6,14)	0	0	1 (1,6,9,17)	0	0	1 (1,9,10,20)
6-PO0	0	0	0	0	0	0	0	0	1 (1,2,4,9,10,12,20)
7-CA1	0	0	0	1 (4,7,15)	1 (5,7,16)	0	0	1 (3,8,11,19)	1 (3,9,11,20)
8-MA0	0	1 (4,5,13)	1 (5,14)	1 (5,15)	1 (5,16)	1 (6,17)	1 (7,18)	0	0
9-SI0	0	0	0	0	0	0	1 (1,2,7,9,10,18)	0	1 (1,2,4,9,10,12,20)

0—conversion period is infeasible, 1—conversion period is feasible. In brackets: years in the conversion period when there will be a cork harvest in the unit

same age class. The former correspond to Model I and the latter to Model II variables as defined by Johnson and Scheurrman (1977). In these models, the temporal arrangement of harvests plays the dominant role and stands are often aggregated into analysis areas (Borges et al. 1999). Nevertheless, the spatial arrangement of harvests must also be considered when addressing both operational and environmental concerns. Spatial resolution and stand-level decisions are receiving renewed attention because the call for an ecosystem based management approach has increased the complexity of planning (Rose et al. 1995). Zell et al. (2004) used recently a Model I model to allocate areas within a stand to specific management strategies.

Both heuristics (e.g., Borges et al. 2002) and mathematical programming approaches (e.g., Martins et al. 2005 and Constantino et al. 2008) have been proposed to address simultaneously the spatial and the temporal arrangement of harvests. Borges and Hoganson (1999, 2000) pointed out the importance of stand design to address spatial optimization concerns. The possibility of integrating the processes of stand design and spatial optimization was further discussed by Heinonen et al. (2007).

The proposed hierarchical approach to cork oak forest management planning took advantage of the integrated functionality of current LP approaches and geographical information systems (GIS) to address stand design and forest regulation. Both inventory data from 313 plots (about 1.5% of cork oak area) and spatial data from the project impact area were used to test the proposed approach. The GIS was used for reclassification of farm land into equally productive management units. Stand design was instrumental to enable the achievement of even flow and ending inventory goals. LP provided the means to optimize financial returns while regulating the cork oak forest. Traditional LP Model I and Model II approaches assign (stand or forest) areas to specific prescriptions and do not guarantee locational specificity. The structure of the proposed LP model guaranteed an integer solution. The LP assignment model selected just one conversion strategy for each management unit (stand).

The proposed approach thus took into account the decision maker's strategic and operational goals. It will avoid current cork extraction annual spatial dispersion and cork uneven flow thus allowing for a sustainable raw-material supply to the cork industry (Pereira and Tomé 2004). The approach proved to be more efficient than classical approaches to forest regulation.

Extensions of the present work might encompass further cork growth and yield modeling (Tomé et al. 1999; Ribeiro and Tomé 2002; Sánchez-González et al. 2005). Moreover, it might encompass the analysis of the correlation between yield and quality (Gonzalez-Adrados and Pereira 1996), between yield and landscape physiographic parameters

Table 4 Solution of the assignment problem: optimum cork harvest schedule for each cork management unit and correspondent net present value (thousand euros)

Cork management unit	Year of age homogeneity satisfied	Cork age (years)	Cork extraction schedule (years in the conversion period)	Cork present value (thousand euros)
AZ0-unit 1	17	9	8 (8), 1 7 (9)	3,011
		8	1 (9), 9 (8), 17 (8)	2,710
		5	6 (11), 17(11)	5,176
BA0-unit 5	14	8	3 (11), 14 (11)	2,258
		7	3 (10), 14 (11)	5,893
		2	6 (8), 14 (8)	2,706
BE0-unit 3	12	8	1 (9), 12 (11)	5,362
		4	4 (8), 12 (8)	6,152
CA1-unit 7	15	5	4 (9), 15 (11)	451
		1	7 (8), 15 (8)	9,973
CA0-unit 4	19	9	8 (8), 19 (11)	2,094
		5	3 (8), 11 (8), 19 (8)	2,347
		6	2 (8), 10 (8), 19 (9)	7,611
		2	8 (10), 19 (11)	1,100
MA0-unit 8	16	4	5 (9), 16 (11)	2,584
		3	5 (8), 16 (11)	8,180
PO0-unit 6	20	9	9 (9), 20 (11)	1,919
		6	2 (8), 10 (8), 20 (10)	7,345
		4	4 (8), 12 (8), 20 (8)	3,130
RO0-unit 2	13	8	3 (11), 13 (10)	1,281
		5	4 (9), 13 (9)	9,677
SI0-unit 9	18	8	1 (9), 9 (8), 18 (9)	417
		6	2 (8), 10 (8), 18 (8)	1,979
		4	7 (11), 18 (11)	1,109
		2	7 (9), 18 (11)	6,072
		1	7 (8), 18 (11)	875

In brackets is the number of years between two consecutive cork extractions (between 8 and 11 years)

(Costa et al. 2008) and between cork oak silviculture (Paulo et al. 2002) and ecological parameters. Further extensions might include the optimization under different scenarios (e.g., biodiversity and carbon-sequestration goals) and the assessment of the sensitivity of the solution to ecological parameters class aggregation schemes.

Conclusions

This paper discussed a hierarchical approach to address cork harvest scheduling operational spatial goals and strategic even flow objectives. The proposed approach combines the use of GIS and mathematical programming. The former is used to enhance land classification and to provide the land basis for an area control approach to regulation. The latter is used to optimize cork harvest scheduling subject to even flow constraints. Results showed that the proposed approach met the management scheduling objectives.

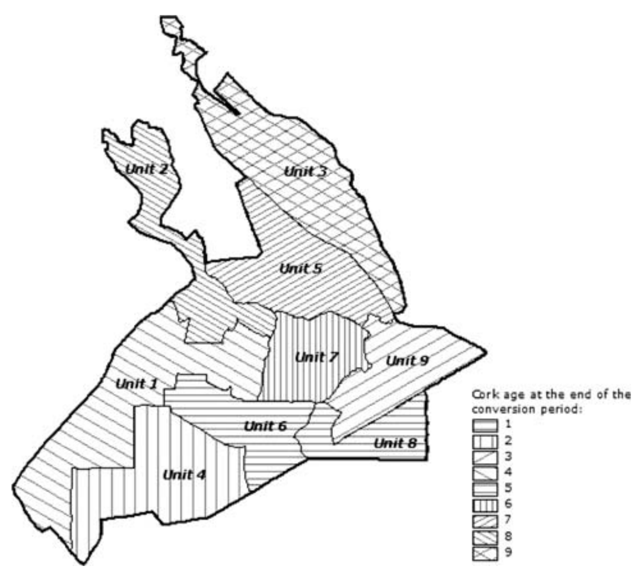

Fig. 4 Optimal solution of the assignment model. To each cork management unit corresponds one unique cork age

Future research will address the improvement of cork oak growth and yield models. It will also focus on the development and assessment of simultaneous approaches to management planning. Finally, it will address other economic and ecological objectives of cork oak forest management planning.

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